An Inverse Radiation Problem for Measurement of Surface Temperature Under Industrial Condition

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Abstract The accuracy of radiative thermometry will be severely affected when emitting-absorbing or scattering media covers the surface to be measured under industrial conditions. An inverse radiation method has been proposed to estimate the true temperature of surface from the measurement temperature of radiation pyrometer in terms of radiation transfer mechanism of participating media. The surface temperature measurement system has been assumed to consist of two infinite parallel, opaque and diffusely emitting and reflecting boundaries, which enclose a participating media. Taking the secondary cooling zone of continuous casting as an example, water vapor and water fog have been chosen as the participating media between surface and pyrometer, and their radiative properties were estimated using box model and Mie theory respectively. The radiative transfer equation of the direct radiation problem has been solved using discrete ordinate method. The inverse problem has been solved by an iteration method on the basis of its related direct radiation problem. The influence of participating media on the monochromatic pyrometer, two-color pyrometer and total radiation pyrometer has been analyzed in the inverse problem. The radiative thermometric models of these three kinds of commonly used radiation pyrometers were based on the Plank law and Stefan-Boltzmann law.

1. Introduction

As a main kind of noncontact temperature measurement method, radiative thermometry has been widely used to measure the surface temperature of high temperature objects, moving objects and the object which is not easy to be closed with under industrial condition, such as the secondary cooling zone of continuous casting process, reheating furnaces, etc [1-3]. But under those industrial conditions, the existence of radiating-absorbing or scattering media, such as water vapor, carbon dioxide, water clouds or fumes between the surface to be measured and radiation pyrometer will seriously affect the accuracy of temperature readings of pyrometer. In order to get the true temperature of this kind of surfaces, a further treatment or correction is necessary. The optical fiber radiation pyrometer and radiation pyrometers with high-velocity airflow blowing equipment have been widely applied to decrease or avoid the influence of participating media in industrial situ [3-4], and only a few works were focused on obtaining the true surface temperature by considering the existence of participating media [5]. No report about the influence of participating media on the radiative thermometry in terms of the radiation transfer mechanism has been found in the presently available literature. The purpose of this study is to present an inverse radiation method to evaluate the true temperature of the high temperature surface which is covered by participating media from the measurement temperature of pyrometer.

Thermal radiation in participating media plays an important role in the transport of thermal energy in high temperature systems. For a general radiation problem, the equation of radiative transfer, source term or temperature distribution of medium, the radiative properties of medium, and the boundary conditions are given, and the radiation intensities are to be determined. In an inverse radiation problem, either the radiative properties, or the source term or temperature distribution of medium, or the boundary conditions are to be determined from the knowledge of the measured data. Inverse radiation problems have numerous engineering applications in a variety of field, such as the remote sensing of atmosphere, the prediction of temperature of combustion process in furnaces, the estimation of radiative properties for solid or porous materials and systems which are not easy to make interior measurement, etc. A wide range survey of literature shows that the inverse radiation problem was mainly about the estimation of radiative properties, temperature or the estimation of both of them simultaneously by iteration or optimizing methods [6-14]. Li and Osizik[6-8], Liu[9,10], Padakannya[11] solved the inverse radiation problem using conjugate gradient method, genetic algorithm and Levenberg-Marquardt method, respectively. The iteration method was firstly used by Chahine [12,13] to determine the temperature profile of the atmosphere, and was used by Tan [14] later. It is worthy of note that both of the two methods are based on the solution of their direct radiation problems, which may be generally solved by Zonal method, Monte-Carlo method, Spherical Harmonics method or Discrete Ordinate method [15-17].

In this work, we simplified the surface temperature measurement system as a one-dimensional azimuthally symmetric radiation problem of emitting, absorbing or scattering medium between two infinite plane parallel slabs. Knowing the temperature of both slabs and the radiative properties of media, the determination of the radiative intensity distribution and the pyrometer temperature would constitute the solution of our direct radiation problem. The inverse radiation problem proposed in this work is to estimate the true temperature of the high temperature surface from the radiation pyrometer measurements, and it can be regarded as a kind of inverse radiation problems of boundary condition estimation. The radiative transfer equation of the direct problem was solved using the discrete ordinate method, and the inverse problem was solved by the iteration method on the basis of the direct model. The temperature measurement in the secondary zone of continuous castings was taken as an example. Water vapor and water fog were the participating media and their radiative properties were estimated using box model and Mie theory respectively. The radiative thermometric models of three kind of pyrometers, monochromatic pyrometer, two-color pyrometer and total radiation pyrometer, were set up on the basis of Plank law and Stefan-Boltzmann law, and the influence of participating media on those pyrometers were analyzed in the inverse problem.

2. Direct Problem

2.1 Statement of the problem

As illustrated in Fig.1, the surface to be measured and its surroundings have been represented by two infinite parallel slabs S_1 and S_2, the pyrometer was vertically faced the high temperature surface S_1 and can be located in any place between the two slabs where it can work very well. The coordinate schematic diagram of this plane-parallel system is shown in Fig.2. The spectral radiative transfer equation (RTE) for this azimuthally symmetric condition is expressed by the following [15-17]:

$$\mu \frac{\partial I_\nu(x,\mu)}{\partial x} = k_{a\nu} I_{b\nu} - k_{e\nu} I_\nu(\tau,\mu) + \frac{k_{s\nu}}{2}\int_{-1}^{1} \Phi_\nu(\mu,\mu') I_\nu(x,\mu') d\mu' \quad (1)$$

where x is the geometric variable; μ is the cosine of the angle between the direction of the radiation intensity and the positive x axis; $k_{a\nu}$, $k_{s\nu}$ and $k_{e\nu}$ are the spectral absorbing, scattering and extinction coefficients of participating media, respectively; $\Phi_\nu(\mu, \mu')$ is the spectral scattering phase function; $I_\nu(x, \mu)$ is the spectral radiative intensity; $I_{b\nu}$ is spectral blackbody intensity, which is given by Planck's law[15-17]:

$$I_{b\nu} = \frac{2h\nu^3 n^2}{c_0^{\,2}\left(\exp(c_2\nu/c_0 T) - 1\right)} = \frac{2h\nu^3 n^2}{c_0^{\,2}\left(\exp(h\nu/kT) - 1\right)} \quad (2a)$$

where h is the Plank constant, ν is spectral frequency, n is the refractive index, c_0 is the speed of light in vacuum, k is the Boltzmann's constant. The total blackbody intensity I_b can be determined by integrating $I_{b\nu}$ over the entire wavelength spectrum, resulting in Stefan-Boltzmann law [15-17] as follows:

$$I_b = n^2 \sigma T^4 / \pi \quad (2b)$$

where σ is Stefan-Boltzman constant.

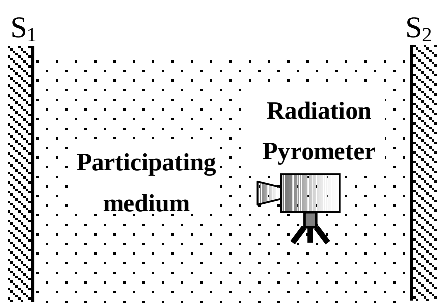


Fig.1 Physical system schematic of the radiative thermometry problem

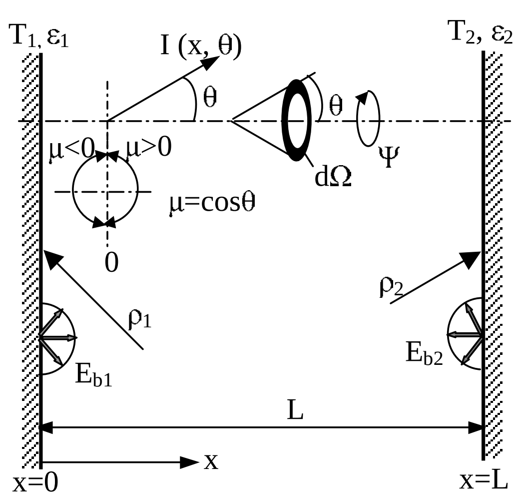


Fig.2 Coordinates schematic diagram of plane-parallel system

To solve Eq. (1), the following opaque, diffusely emitting and reflecting boundary conditions are set at x=0 and x=L respectively:

$$I_v(0,\mu) = \varepsilon_1 I_{bv}(T_1) + \frac{\rho_1}{\pi}\int_{-1}^{0} I_v(0,\mu')\mu' d\mu' \ , \ \mu > 0 \tag{3a}$$

$$I_v(L,\mu) = \varepsilon_2 I_{bv}(T_2) + \frac{\rho_2}{\pi}\int_{0}^{1} I_v(L,\mu')\mu' d\mu' \ , \ \mu < 0 \tag{3b}$$

where ε_1 and ε_2 , ρ_1 and ρ_2 are the emissivity and reflectivity of the slab S_1 and S_2 respectively, and $\varepsilon_1 + \rho_1 = 1$, $\varepsilon_2 + \rho_2 = 1$.

In addition, the temperature distribution in the participating media is necessary to solve Eq. (1) and (3). Because the response time of pyrometer is very short at the moment of temperature measurement, we can assume the system is under radiative thermal equilibrium and its radiative energy equation can be written as:

$$\int_0^\infty k_{av}\left[4\pi I_{bv}(x) - G_v(x)\right]dv = 0 \tag{4}$$

where $G_v(x)$ is spectral incident radiation:

$$G_v(x) = \int_{4\pi} I_v(x,\mu)d\Omega \tag{5}$$

It shows that the solving of Eq. (1), (3), (4) is an iterative procedure and the temperature distribution and radiative intensity field can be obtained at the same time.

2.2 Radiative properties of participating media

In the RTE Eq. (1), parameters needed for the participating media are coefficients k_{av}, k_{sv} k_{ev} and the phase function $\Phi_v(\mu, \mu')$. As we known, radiative properties of participating media are often very non-gray or strong spectral dependency, so the gray media assumption is unacceptable in most cases.

Radiative properties of water vapor. For gas media, the scattering can be neglected, that is to say it satisfies $k_{sv} = 0$ and $\Phi_v(\mu, \mu')=0$. The absorption coefficient of gas can be estimated by many methods or models, such as Line-by-line method, statistics narrow band model (SNBM), exponential wide band model(EWBM), etc.[15-18]. But an enormous calculation time and the necessary database are required to execute the methods above.

For the sake of simplicity, a simplest spectral band model, the box model [15,17,18] has been chosen. Comparing with the commonly used gray band approximation of SNBM and EWBM, the box model can estimate the radiative heat transfer of gas almost equally well [19]. In the box model, the absorption coefficient was assumed to be constant in the band and was related with band intensity S_k and effective bandwidth $\overline{\Delta w_k}$. At partial pressure P and temperature T, the absorption coefficient $\bar{k}_{a\Delta v k}$ (1/m) of the k^{th} spectral band of gas can be written as [17]:

$$\bar{k}_{a\Delta v k}(T) = [S_k(T)/\overline{\Delta w_k}]\cdot P = [S_k(T_0)T_0/T]/\overline{\Delta w_k}\cdot P = \frac{T_0}{T}\cdot\frac{S_k(T_0)}{\overline{\Delta w_k}}\cdot P \tag{6}$$

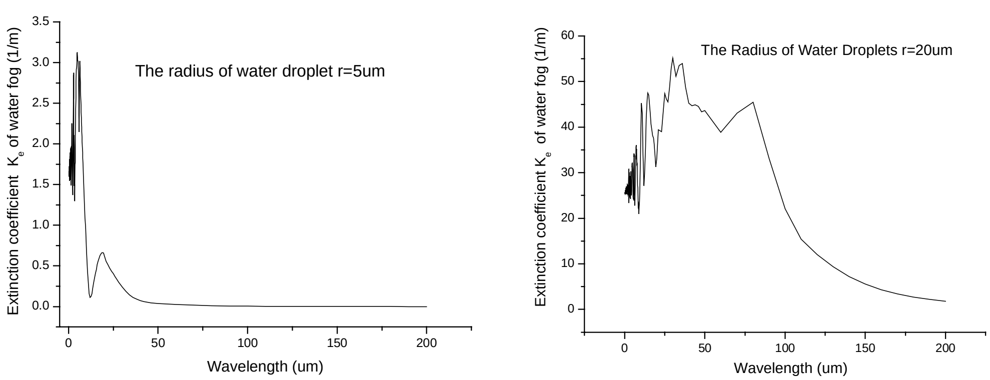
Radiative properties of water fog. Radiative properties of water droplets have been obtained by Mie theory [15,16,20] in this work. Supposing that the water fog is monodispersed, then the coefficients k_{av}, k_{sv} and k_{ev} are given by the following relations:

$$k_{ev} = N_T \pi r^2 Q_{ext} \qquad k_{sv} = N_T \pi r^2 Q_{sca} \qquad k_{av} = k_{ev} - k_{sv} \tag{7}$$

where N_T is the number of particles per volume, r is the size of droplet, Q_{ext}、Q_{sca} and Q_{abs} are the absorption, scattering and extinction efficiency calculated by Mie theory with available optical constant of water [21]. For the sake of clarity, their definitions are not listed here. For our practical computations, the exact Mie phase function involving heavy calculations, is approximated by the linear phase function [15]:

$$\Phi(\Theta) = 1 + a_0 \cos(\Theta) \tag{8}$$

where Θ is the scattering angle, a_0 is a constant equals to –1, 0 and 1 for backward scattering, isotropic scattering and forward scattering respectively. Supposing that the radius of water droplets is 5μm or 20μm, $N_T=10^4/cm^3$, its extinction coefficient is shown in Fig.3. As can be seen from Fig.3, the radiative properties of water fog are strongly nongray, so we have to solve the Eq.(1) by dividing the wavelength into numbers of spectral interval Δν, which is similar with the spectral band model of gas radiation.



(a) (b)

Fig.3 Extinction coefficient of monodispersed water fog

2.3 Calculation of spectral band intensity and temperature

Corresponding with the radiative properties of molecular gas and particular media, RTE can be solved on a spectral band. Integrated Eq. (1) over a spectral interval Δν, i.e. the operator $\int_{\Delta v} (\cdots) dv$ is applied as follows:

$$\mu\frac{\partial I_{\Delta v}(x,\mu)}{\partial x}=\bar{k}_{a\Delta v}\cdot I_{b\Delta v}-\bar{k}_{e\Delta v}\cdot I_{\Delta v}(x,\mu)+\frac{\bar{k}_{s\Delta v}}{2}\int_{-1}^{1}\Phi_{v}(\mu,\mu')I_{\Delta v}(x,\mu')d\Omega \tag{9}$$

where $I_{\Delta v}(x,\mu)=\int_{\Delta v}I_{v}(x,\mu)dv$, $\bar{k}_{a\Delta v}=\int_{\Delta v}k_{av}dv$, $\bar{k}_{s\Delta v}=\int_{\Delta v}k_{sv}dv$, $\bar{k}_{e\Delta v}=\int_{\Delta v}k_{ev}dv$, $I_{b\Delta v}=\int_{\Delta v}I_{bv}dv$. And $I_{\Delta v}$ is the spectral band intensity, $\bar{k}_{a\Delta v},\bar{k}_{sv}$ and $\bar{k}_{ev}$ are spectral band absorption, scattering and extinction coefficients, $I_{b\Delta v}$ is the blackbody spectral band intensity, Plank function within each band is

$$I_{b\Delta v}=I_{b}\cdot F_{\lambda_1 T-\lambda_2 T}=\frac{n^2\sigma T^4}{\pi}\left(F_{0-\lambda_u T}-F_{0-\lambda_l T}\right) \tag{10}$$

The term in the parenthesis is the fractional function between the upper and lower limits of the band. In numerical programming use the fitted polynomial relations [16]:

$$F_{0-\lambda T}=\frac{15}{\pi^4}\sum_{u=1,2,\cdots}\frac{e^{-un}}{u^4}\{[(un+3)un+6]un+6\}\quad (\mathrm{n}=14388/\lambda\mathrm{T}) \tag{11}$$

By discrete ordinate method [15], Eq.(9) is evaluated for a discrete number of directions μ_j of weight w_j and the integral term in it is replaced by a numerical quadrature as follows:

$$\mu_j\frac{\partial I_{\Delta v\,i,j,k}}{\partial x}=\bar{k}_{a\Delta v\,k}\cdot I_{b\Delta v\,k}-\bar{k}_{e\Delta v\,k}\cdot I_{\Delta v\,i,j,k}+\frac{\bar{k}_{s\Delta v\,k}}{2}\sum_{j'=1}^{N}w_{j'}\Phi_{j,j'}I_{\Delta v\,i,j',k} \tag{12}$$

Similarly, the spectral band form of boundary condition Eq.(2) and Radiative equilibrium energy equation Eq.(4) by discrete ordinate technique are given by:

$$I_{\Delta v_{i=1,j,k}}=\varepsilon_1 I_{b\Delta v}(T_1)+\frac{(1-\varepsilon_1)}{\pi}\sum_{\substack{j'=1\\ \mu_{j'}<0}}^{N}w_{j'}\mu_{j'}I_{\Delta v_{i=1,j',k}}\ ,\ \mu_j>0 \tag{13a}$$

$$I_{\Delta v_{i=M,j,k}}=\varepsilon_2 I_{b\Delta v}(T_2)+\frac{(1-\varepsilon_2)}{\pi}\sum_{\substack{j'=1\\ \mu_{j'}>0}}^{N}w_{j'}\mu_{j'}I_{\Delta v_{i=M,j',k}}\ ,\ \mu_j<0 \tag{13b}$$

$$4\pi\sum_{k=1}^{nk}\bar{k}_{a\Delta v_k}\frac{\sigma T_i^4}{\pi}(F_{0-\lambda_{u_k}T_i}-F_{0-\lambda_{l_k}T_i})-\sum_{k=1}^{nk-1}\bar{k}_{a\Delta v_k}\left[\sum_{j=1}^{N}w_j I_{\Delta v_{i,j,k}}\right]=0 \tag{14}$$

where i =1, 2, 3,…, M, and M is the number of control volume in spatial direction; j =1, 2, 3, …, N, and N is the number of discrete direction in angular direction of DOM; k = 1, 2, …… nk, and nk is the number of spectral band Δν. The set of differential Eq.(12~14) is solved by selecting a spatial discretization scheme and the spectral band intensity $I_{\Delta v}$ and the temperature distribution in the media can be found in an iterative manner.

2.4 Radiative thermometric models

Thermometry models of pyrometer are based on the Plank law Eq.(2a) and Stefan-Boltzmann law Eq.(2b). Knowing the spectral band intensity $I_{\Delta\nu}$, the indicated temperature of pyrometers can be obtained by collecting the local thermal radiation energy. Because the spectral response of radiation pyrometers is not a specific wavelength but a small spectral band interval $\Delta\nu$ from ν_1 to ν_2, the temperature formulations for monochromatic pyrometer, two-color pyrometer and total radiation pyrometer should be written in spectral band form respectively:

$$E_{\Delta\nu}(T') = \varepsilon E_{b\Delta\nu} = \varepsilon\pi I_{b\Delta\nu} \tag{15}$$

$$E_{\Delta\nu 1}(T') / E_{\Delta\nu 2}(T') = E_{b\Delta\nu_1} / E_{b\Delta\nu_2} \tag{16}$$

$$E_{0\sim\infty}(T') = \varepsilon E_b = \varepsilon \sum_{\Delta\nu} E_{b\Delta\nu} = \varepsilon n^2 \sigma T'^4 \tag{17}$$

where $I_{b\Delta\nu}$ can be determined by Eq.(10) or the integrated form of Plank function Eq.(2a). The terms in the left side of Eq. (15~17) are the spectral band radiation emissive power and can be evaluated from intensity $I_{\Delta\nu}$ using discrete ordinate method:

$$E_{\Delta\nu i,j,k} = \sum_{j=1,\mu_j>0}^{N} \mu_j w_j I_{\Delta\nu i,j,k} \tag{18}$$

The indicated temperature of pyrometers may be calculated by Eq.(15~17) using Eq.(18).

3 Inverse Problem

On the basis of aforementioned direct radiation problem, the purpose of our inverse radiation problem is estimating the true temperature T_1 of surface S_1 from the measurement temperature T_{1mea} of radiation pyrometer. The detail steps of the inverse problem are shown in Fig.4.

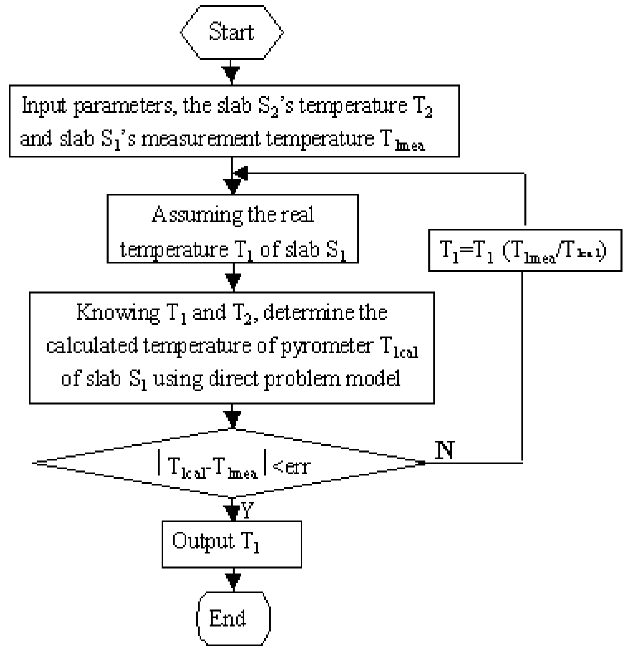


Fig.4 Flow chart of the inverse problem

4 Results and discussion

Considering the different radiative properties of gas and particulate media, their influence on the radiative thermometry for the surface temperature measurement problem has been analyzed. The response spectral band of pyrometer in our calculation is based on the MR1S thermometer of Raytek Co., that is 0.75~1.1μm for monochromatic and 0.75-1.1μm, 0.95~1.1μm for two-color pyrometer. It has been taken that the distance L between the two slabs is 1.0m, the temperature T_2 of slab S_2 is 400˚C, and the true temperature T_1 of the surface S_1 is 1200˚C. The measurement temperature T_{1mea} indicated by the pyrometers has been taken from the calculated temperature T_{1cal} of the direct problem. According to the inverse problem, the true temperature T_1 of the surface S_1 may be obtained from the indicated temperature T_{1mea}.

4.1 Water vapor

The participating media between the two infinite parallel slabs is pure water vapor at 1atm. The emissivities of S_1 and S_2 are chosen to be 0.5,0.8,1.0 respectively in order to analyze its effect on the inverse problem.

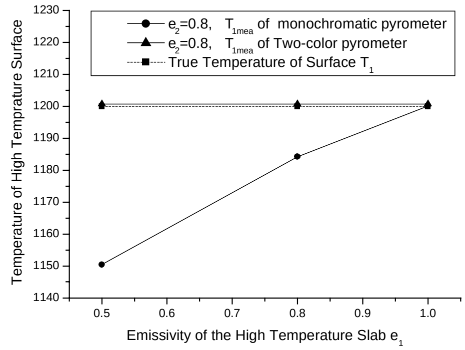


Fig.5 Surface temperature of monochromatic and two-color pyrometer (ε_1 is different)

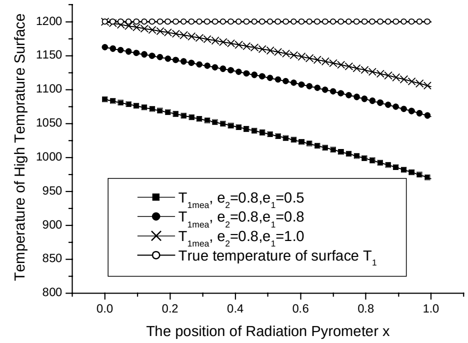


Fig.6 Surface temperature of total radiation pyrometer (ε_1 is different)

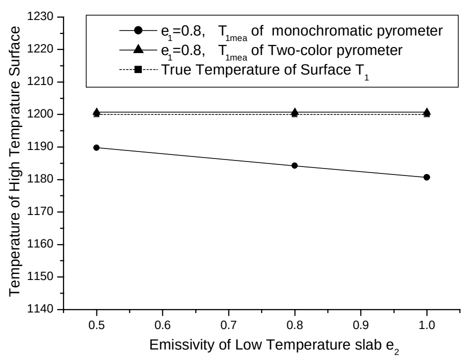


Fig.7 Surface temperature of monochromatic and two-color pyrometer (ε_2 is different)

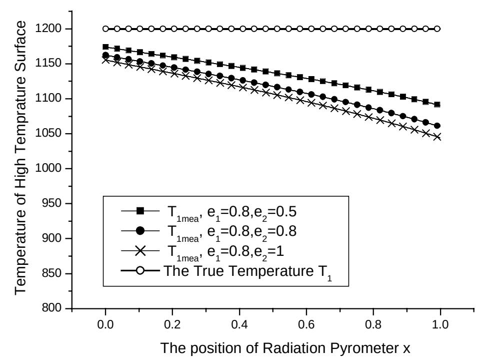
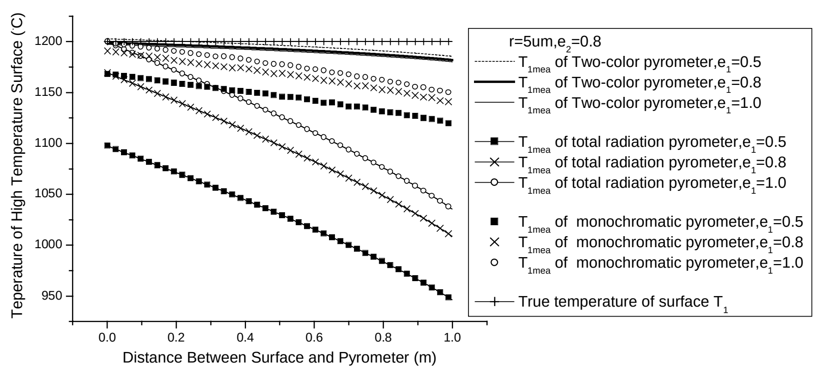


Fig.8 Surface temperature of total radiation pyrometer (ε_2 is different)

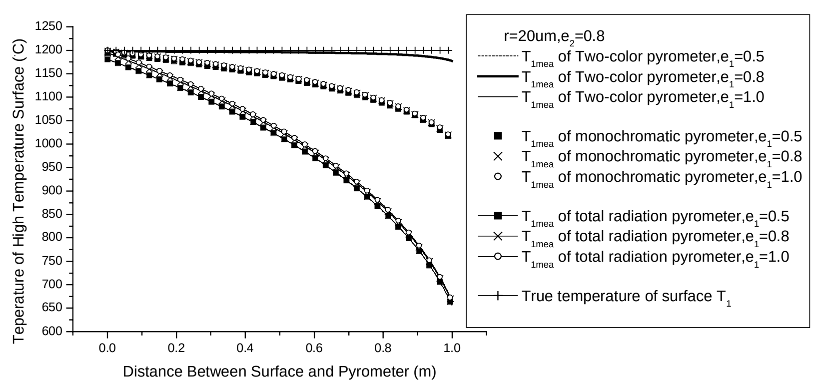
Fig.5~8 show the measurement and true temperatures of the high temperature surface S_1. As far as monochromatic and total radiation pyrometers are concerned, the larger emissivity ε_1 is, the closer the measurement temperature and the true temperature are. On the contrary, with the increasing of emissivity ε_2, the difference between the measurement temperature and the true temperature is increased. The measurement temperature of two-color pyrometer is independent of emissivities ε_1.and ε_2. Furthermore, because the response spectral band of monochromatic and two-color pyrometer falls in the non-absorbing spectral band of water vapor, the water vapor itself has no influence on the measurement temperature. But for the total radiation pyrometer, the larger the thickness of water vapor is, the smaller the measurement temperature is. The reason is that the total radiation pyrometer is based on collecting the radiation energy of whole wavelength and water vapor may attenuate the radiation energy on some spectral band. All in all, the two-color pyrometer is the most exact one among these three kinds of pyrometers and the total radiation pyrometer is severely influenced by water vapor.

4.2 Water fog

Fig.9~11 illustrate the variation of the measurement temperature and the true temperature of surface S_1 with the emissivity ε_1 and ε_2 for various distance between surface and pyrometer when the participating media is water fog. As can be seen from Fig.9 and Fig.10, for the monochromatic and total radiation pyrometers, the difference between the measurement temperature and the true temperature decrease with the emissivity ε_1 and increase with emissivity ε_2, and it is the same as the water vapor. For the two-color pyrometer, Fig.11a indicates that the difference between the measurement temperature and the true temperature increase with emisivity ε_1, and Fig.11b shows that the difference doesn't increase or decrease with the emissivity ε_2, but related with the position of pyrometer. In addition, because of the continuous radiative properties of water fog, the measurement temperature of the three kinds of pyrometers is related with the thickness of water fog. The difference between the measurement and true temperatures increased with the distance between surface and pyrometer. It can also be noted that emissivities ε_1 or ε_2 do not affect the pyrometers very obviously for the water fog with bigger droplets radius (r=20μm) as the extinction coefficient of it is very big and is the key influence factor of the temperature measurement system.

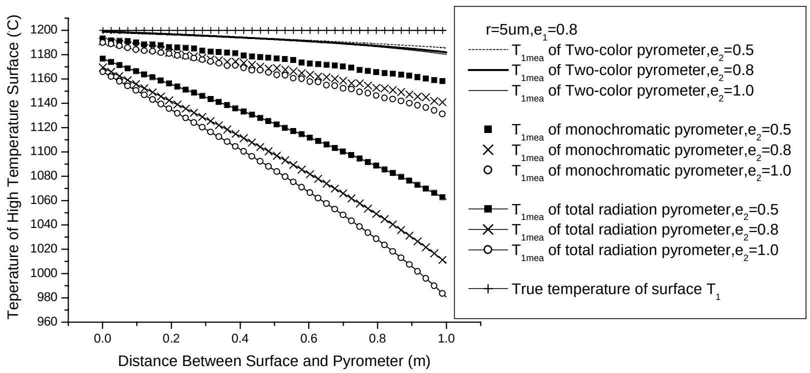


(a) r=5μm

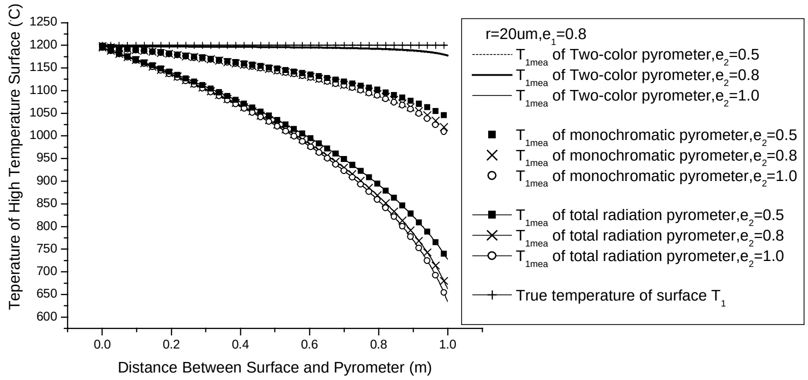


(b) r=20μm

Fig.9 Surface temperature of radiation pyrometer (ε_1 is different)

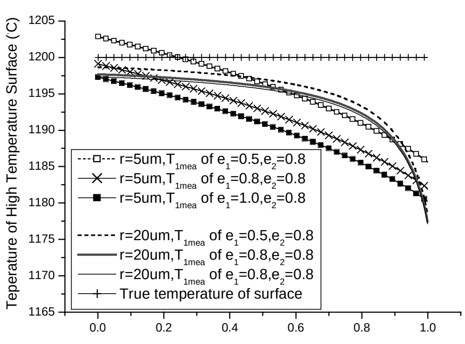


(a) r=5μm

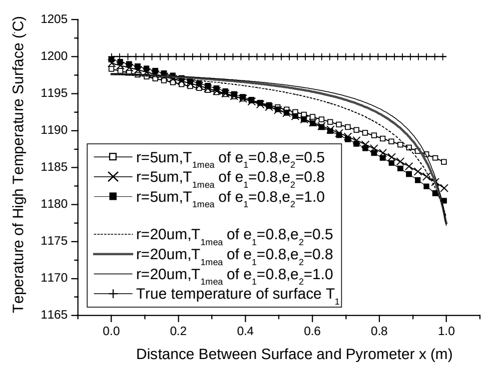


(b) r=20μm

Fig.10 Surface temperature of radiation pyrometer (ε_2 is different)



(a)



(b)

Fig.11 Surface temperature of two-color pyrometer

5 Conclusion

One-dimensional inverse radiation problem for the measurement of surface temperature under industrial conditions was established in this work. The problem was based on the radiative transfer of participating media and the basic law of radiative thermometry, and was solved using iteration method on the basis of the direct radiation problem, which has been solved by discrete ordinate method. The influence of gas and particulate media on the radiation pyrometer was analyzed. It can be concluded that for the particular media the radiative properties (extinction coefficient) and the thickness of media (the distance between surface and pyrometer) are more important than the emissivity of high or low temperature slabs. The measurement temperatures of monochromatic pyrometer, two-color pyrometer and total radiation pyrometer need to be treated using the inverse method to get the true temperature of surface. For gas media, the total radiation pyrometer has the similar situation with that of particular media. Among these pyrometers, the error between the measurement temperature and the true temperature of two-color pyrometer is the smallest. To carry out further investigation, experiment verification is necessary because our measurement temperature in the theoretical analysis is taken from the calculated temperature of direct problem.

Acknowledgment

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